Influence of the modulation instability on the formation of super-continuum in tapered and cobweb fibres

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Abstract: Numerical modelling and study has been conducted of the specific properties of super-continuum generation in tapered and cobweb fibers for different pump pulse lengths. For the first time the key role of the modulation instability in continuum formation has been pointed out both for long (> 1 ps) and short (~100 fs) pump pulses.

1. Introduction

The effect of super-continuum (SC) generation which consists in significant widening of the pump radiation spectrum upon passing through a non-linear medium was first observed in the end of sixties by Alfano and Shapiro [1]. In recent years, this effect has been a topic of immense interest with many research groups in connection to development of photonic crystal fibres and tapered fibres. Such fibres made possible SC generation with spectrum width covering more than two octaves while using comparatively small powers of pump radiation [2,3]. By the present moment, SC has found its applications in a number of fields important both in scientific and in practical aspects. Among these fields one may mention specifically the optical frequency metrology [4], optical tomography [5], and telecommunications [6]. Meanwhile, the SC generation effect itself remains a subject of active studies aimed both at the research of different properties of SC radiation, SC optimisation for various applications, and at identification and thorough understanding of mechanisms that are at work in formation of wide radiation spectrum. In-depth studies of the role played by different effects in SC generation exhibit a number of viewpoints, sometimes entirely at variance with each other. This is the case of the stimulated Raman scattering (SRS) effect [7,8 vs. 9,10] and self phase modulation (SPM) effect [9,10 vs. 11,12]. Apart from this, predictions of the commonly used in a few recent years model of SC generation by soliton fission give indications of certain discrepancies in comparison to experiment [10,13].

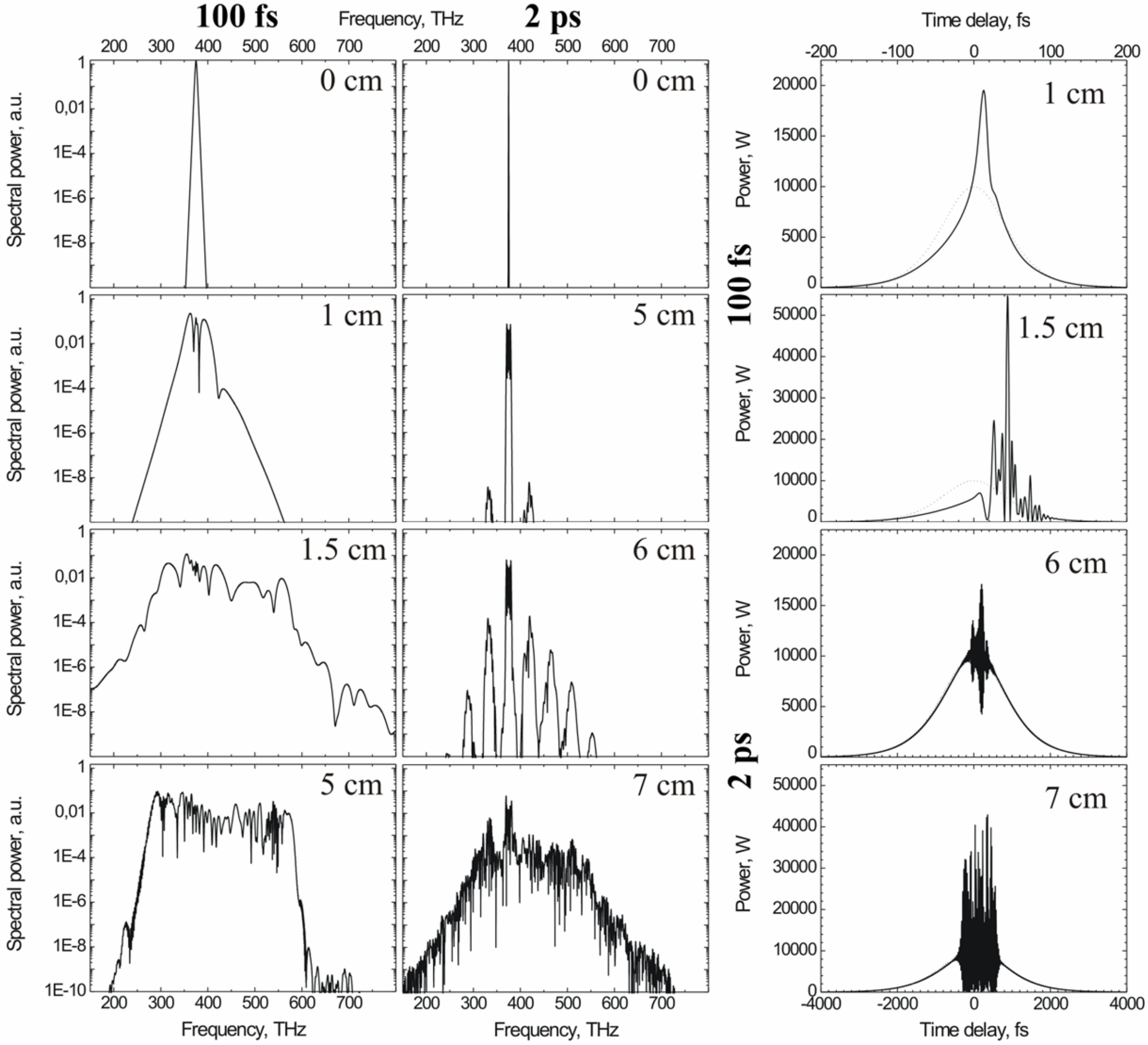
In the present work, the SC generation in micro-fibres pumped by multi-soliton pulses of different duration is explored by numerical modelling. The modelling itself is based on the solution of generalised non-linear Schrödinger equation (GNLSE) for pump pulses propagated through a quartz 2.2-µm core surrounded by air. This model is valid not only for tapered fibres, but also for photonic crystal fibres, and even more so for cobweb fibers, in which the central quartz core is almost fully enclosed by air. [7]. Despite the fact that the dependence of SC and its properties on the duration of the pump pulses has been discussed by a number of authors [12,13], this present work to the best of our knowledge gives for the first time a comparative analysis of SC generation specific features observed under short pulse (50–200 fs) and under long pulse (picosecond) pumping in the abnormal dispersion domain of the fibre. In this analysis a single spectral broadening mechanism is assumed, the modulation instability (MI) that arises from the noise in case of long pumping pulses, whereas in case of short pump pulses it is generated by SPM and compression of multi-soliton pulses. The present report discusses for the first time the MI mechanism as the primary one for SC generation in spite of the fact that MI initiated by SPM has been long known [14]. Suggested in this work approach to spectral broadening of SC as mainly caused by MI allows in particular to better understand the results of comparative study of SC coherent properties exhibited when pumped with pulses of different duration [12,13].

2. Numerical model

For numerical modelling of the SC generation effect in the present work the authors use GNLSE [15]:

$$\frac{\partial A}{\partial z} = i\sum_{k=2}^{k_{\max}} \frac{i^k}{k!}\beta_k \frac{\partial^k A}{\partial t^k} + i\gamma\left(1 + \frac{i}{\omega_0}\frac{\partial}{\partial t}\right)\left(A(z,t)\int_0^\infty R(t')\left|A(z,t-t')\right|^2 dt'\right) \qquad (1)$$

where $A(z, t)$ – electric field envelope, , β_k – dispersion coefficients at the pump frequency ω_0 , and $\gamma = n_2\omega_0/(A_{eff}c)$ – non-linear coefficient, where $n_2 = 3.2\times10^{-20}$ m^2/W – non-linear refractive index of quartz and A_{eff} – effective cross-section of the fundamental mode. The kernel $R(t)$ of the integral operator for non-linear response of the medium was taken from experiments referenced in [16]; it contains both electronic and vibrational (Raman) components. Equation (1) was derived without resorting to approximation of slowly varying amplitudes; in the process of reduction the assumption of the fundamental mode only propagated through the fibre was used, the latter assumption being based on the axial symmetry of the experimentally observed by us transverse distribution of the radiation at the output from the fibre. Expansion of the dispersion operator into the Taylor series in frequency was carried out to the highest term with $k_{max} = 5$. The second item in the right-hand side of equation (1) is responsible for a number of non-linear optical effects such as SPM, MI, SRS, four-wave mixing (FWM), self-steepening and shock formation [15].



3. Simulation results and discussion

In Fig. 1, the calculated spectra (left) and continuum intensity dependence on the time (right) are given for pump pulses of duration T_0 = 100 fs and 2 ps, after propagation through various lengths of the micro-fibre. The corresponding values for duration are shown on top of the spectra and to the left of the *I(t)* plots; pulse travel distance *z* is specified in each plot. The spectra are plotted in a log scale on the power axis, the time axes being linear. Peak power of the pumping pulses is taken 10 kW, wavelength is 800 nm (corresponds to the frequency 375 THz), the wavelength of the zero dispersion in the micro-fibre is around 740 nm.

For 2-ps pump pulses, SC generation sets in with noise amplification (or with amplification of pump pulse wings as is the case in our study) because of MI. In the process, on both sides of the pump line two new spectral lines are generated (Fig. 1, T_0 = 2 ps, z = 5 cm). As the pulse travels further down the fibre (z = 6 cm) these lines grow stronger and other lines emerge, perhaps prompted by FWM effect. The whole spectrum demonstrated a certain asymmetry: peaks in the domain of frequencies higher than that of the pump pulse rise higher than those in the low-frequency domain. Following the fibre further, at z = 7 cm, radiation intensity starts growing in between the emerged peaks so that finally these peaks blend into a single continuum spectrum. This blending process can be also attributed to MI: by z = 6 cm, an instability in the pump pulse develops (see the *I(t)* plots in Fig. 1) so that the peak power value grows higher by half and by z = 7 cm it grows fourfold. Qualitatively it must lead to a shift combined with broadening of the gain line, this effect giving rise to the growth of spectral components located in gaps between generated peaks. Broadening of individual lines because of SPM does not play a significant part here since it occurs much slower as compared to the exponential development of instability. A somewhat different situation takes place in case of short (T_0 = 100 fs) pumping pulses. Widening of the pump spectrum because of SPM (compression of multi-soliton pump pulses) happens by a factor of 20 faster than for 2-ps pulses, so that by reaching z = 1 cm the spectrum starts bridging gaps between gain lines formed by MI. This results in rapid (within several millimetres of fibre between z = 1 cm and 1.5 cm) development of MI, which in this case springs not from the noise, but rather from the pump pulse itself broadened by SPM. The width of the ultimately generated spectrum is approximately the same as that observed under T_0 = 2 ps. In the temporal representation, the SC generation is not characterized in this case by emerging oscillations with growing amplitude on the background of virtually unchanged shape of the pump pulse as it happens under long (2-ps) pump pulses. Now it is typical to observe strong non-linear compression (which is directly related to the spectrum broadening) and subsequent fast decay.

3. Conclusion

In the framework of this approach to SC generation mechanisms, it becomes evident why there is a contradiction between the calculated in [12] higher degree of SC coherence for short pulses and experimental data from [13]. This comes from the fact that in [12] quantum noise only was taken into consideration, whereas pulses themselves were assumed stable. Since with short pulses SC develops from the spectrum of the pump pulse itself broadened by SPM, noise does not play a major role and the degree of coherence obtained in calculations is close to unity. When pulse duration is increased the length of fibre necessary for generation of a spectrum with specific width because of SPM grows accordingly, hence more noise amplification through MI takes place, which naturally leads to reduction of the coherence degree of the generated SC. From this discussion it follows that for a valid description of experimental results the model must take into account, apart from the quantum noise, also fluctuations of the parameters of pump pulses (for instance, its energy). When answering the practically important question, whether it is short or long pump pulses that result in a cleaner continuum with less noise, one must take into account a certain relation between quantum noise and fluctuations of the pumping pulse parameters.

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